Structural flood damage and the efficacy of property-level interventions

Abstract

- **Purpose:** To investigate the flood impact on a detached dwelling based on physical attributes related to the positioning, form and orientation of the house. To investigate the effectiveness of property-level interventions (PLP) to mitigate the direct structural damage of the house and the degree of flood water ingress within the house.
- **Design/methodology/approach:** The methods included modelling and simulation within the ANSYS Fluent® CFD software. Flooding scenarios with constrained parameters using theoretical modelling methods/tools were used to test the research hypotheses. Therefore the results obtained will match the what-if scenarios considered if/based on the standard equations and assumptions made i.e. – the idealised model.
- **Findings:** It was found that the position, orientation and form of an individual dwelling with brick and block construction, informs the impact of the applied pressure on the structure and water ingress. Increase in pressure on the structure was noted from 0.3m. All examined PLP mitigated the risk of structural damage if applied in consideration with other interventions e.g. mortar sealing. The use of non-return valves could potentially increase the pressure on the structure, but was also found to be effective in reducing water ingress. Findings should be considered in conjunction with the assumptions and exceptions of this study.
- **Research limitations/implications:** Limitations are that the findings are based on an idealised model of a single detached house, with no landscape obstruction to the watercourse. This mathematical approach concerned with developing the normative models may therefore not fully describe the real world's complex phenomena. But it provides the first vision and an objective basis to explore the questions under study, and to propose usable outputs. Flooding caused from internal sources (e.g. bursting of pipes, roof leaks) or seepage from the ground and moisture through the walls were excluded. Building content were not modelled.
- **Practical implications:** Common property-level flood interventions are typically tested to mitigate water ingress to the house. This study extends this approach to include the prevention of structural damage to the external walls. This is because, disparate property-level flood prevention solutions without full understanding of their degree of effectiveness or impact on the building's structural integrity. This study is practically significant because it provides outputs and means to examine which intervention(s) are better for delivering flood protection to a standard brick/block detached house type. This knowledge is beneficial for relevant stakeholders who can use it to deliver effective property-level flooding resilience measures.
- **Originality/value:** The study provides the basis for property owners and building professionals to explore and implement appropriate, cost-effective single property-level interventions against flooding. Further, the effective implementation of interventions can be used to achieve a customised, 'fit for purpose' resilience retrofit.

Keywords: flooding, building retrofit, flood damage, flood repair, property-level interventions.

1. Introduction

Flooding poses a significant risk to wellbeing, livelihoods and properties in the UK, Europe and around the globe (Beagle *et al.,* 2014). The Environment Agency (2009) suggested that 5.2 million homes are at risk of flooding in the UK, equating to 1 in 6 homes. It is recognised as one of the most damaging natural hazards, responsible for approximately one third of the total economic losses due to natural hazards in Europe (EEA *et al.,* 2008). These figures are significant, thus holistic understanding and action are needed to ensure that both new and existing buildings, and the built environment as a whole are resilient and adaptive to flooding.

There remains no direct analysis of flood records to prove that the increase in flood events (Figure 1) is influenced by climate change; but this causality is extensively accepted (Robson, 2002). Higher and more intense rainfall has been observed and this trend is expected to continue (Kundzewicz, 2005). This means that flood risk trends are also likely to increase. Hence, flood damage assessments are of growing importance since damage has to be estimated in any deliberation of cost-effectiveness of flood mitigation measures, analyses of vulnerability and resilience, land use planning, flood risk mapping, comparative risk analyses, and financial appraisal (Merz *et al.*, 2010).

Figure 1 Reported flood phenomena in Europe from 1980 to 2010 (EEA, 2016)

Flooding is a sign of urbanisation interacting and disrupting the natural water system (Beagle *et al.,* 2014), especially where permeable landscape has been replaced with hard surfaces for infrastructure (DBW, 2012). Urbanisation is a continuous process and so are flood-damage processes. The latter are influenced by the interplay of various hydro-meteorological, hydrological, hydraulic, and socioeconomic factors (Schroeter *et al.* 2014; Barredo *et al.* 2012). Hence, the increase in flooding has been attributed to a growth of population and wealth in attractive but flood prone areas (Jongman 2015). Further, prevalent building methods and practises further exposes the building and contents to damage in the event of flood. Traditional construction and service installation methods increase the propensity for water ingress through cavities, gaps and holes. This risk is coupled with the significant reliance on macro scale infrastructure and flood defences to provide adequate protection against natural events like storms and floods. Even though recent examples show that these solutions can fail in the wake of unprecedented events. Therefore, a comprehensive resilient solution should consider the macro, meso and micro-level solutions for the built environment.

CIRIA recommends four sequential actions for preparing buildings for a flood event: Avoidance/Prevention; Resistance; Resilience and Repairing (CIRIA, 2007): Avoidance was defined constructing a building and its surrounds in such a way to avoid it being flooded. Resistance is preventing floodwater from entering the building and damaging the fabric. Resilience is reducing the damage impact of flood water entering the building, maintaining structural integrity and facilitating drying, cleaning and; Repairing falls under resilience, and it is making sure elements damage from flooding is easy to repair and replace.

In the UK, the Environment Agency has a priority to increase the public awareness of risk of flooding, and public surveys are carried out regularly to understand levels of awareness (EA, 2009). But the surveys only target the areas with high probability of flooding, which gives a false sense to the areas with lower probability of flooding that their properties are secured from flooding (EA/Defra, 2016). Therefore, more can be done to increase awareness and encourage action to mitigate the consequences of flooding. According to a recent Red Cross study, many residents wished they knew more about the damage of flooding as well as the protections they can do to their properties; only 21% knew information about flood related issues (McNulty and Rennick, 2013). The UK government guidance include advice on how individual house owners can apply property-level protection (PLPs) to protect their properties (EA, Defra, 2015), but not many people are exposed to the information. Uncertainties also exist about the effectiveness of some PLPs to prevent flood damage without causing further damage to be building itself.

This study explores flood resistance and resilience methods for houses. The purpose is to assess the impact of flooding on buildings by measuring the vulnerability and resilience of a typical house, relating the flood damage to two flood characteristics: *flood velocity* and *flood duration*. Then, the efficacy of specific property-level flood protective measures are examined. HR Wallingford, n.d.; BSI, 2016 addresses the problem of water ingress and have designed property-level interventions which can be applied to the exterior of the house quickly and conveniently to make the house watertight. These devices are recognised to be fit for purpose and can be bought by individual house owners easily through online websites (BSI, 2016). As common market flood interventions are tested to ensure the water tightness of the house only, the research aims to make further contribution by exploring the mitigation of structural damage as well as the water tightness of the house. This will help to examine which intervention(s) are best for delivering flood protection to a standard brick/block detached house type. This information will in turn be beneficial for relevant stakeholders who can use it to deliver effective property-level flooding resilience measures.

1.1. Aims and objectives

This study investigates and is limited to flood damage; specifically structural damage and water ingress to a specific detached house typology investigated by modelling and testing the physical attributes related to the positioning, form and orientation of the house. Using building and flooding characteristics, it then examines the effectiveness of property-level interventions currently available in the market to mitigate the direct structural damage of the house and the degree of flooding within the house. The approach to the work is as follows:

- **Literature review** – To understand why flooding is a problem and explore the flood protective measures available.
- **Data production and analysis** – The efficacy of common protective interventions to prevent structural damage as well as avoid water ingress are explored. For this, a typical detached house in a flood-risk area was mathematically modelled in ANSYS Fluent®, a computational fluid dynamics (CFD) tool detailed in the methodology section.
- **Data application** – Protective interventions are then introduced to investigate effectiveness and performance.
- **Output** – The findings provide the basis for a house owner or interested stakeholder to investigate appropriate flooding interventions for their property and make investment decisions to suit. Further, the findings can be used to explore the benefits

of combining multiple interventions to meet a customised, 'fit for purpose' resilience retrofit.

1.2. Scope and limitations

The scope of this study, which may also affect the validity of findings, are as follows: [1] The study is limited to the physical building and context parameters that could influence and result in flood damage to a masonry, detached house.

[2] Although, macro-level surveys (McNulty, Rennick, 2013), physical modelling (HR Wallingford, n.d), as well as mathematical modelling (Kreibich *et al*., 2009) have been used to investigate the effects of floods on buildings and urban areas. The main critique of this mathematically modelling approach is that flood damage modelling is subject to extensive uncertainties. These uncertainties are as a result of limited knowledge about the damaging process and very commonly, models are set up by generalising flood damage factors and aggregating input data (Schroter et al., 2014). This work utilises simulations and modelling approach with constrained parameters to minimise these uncertainties. This implies that further work is required to establish real-life viability and validity.

3] Property-level flood protection (PLP) technologies are broadly classified as: Perimeter technologies; building aperture technologies and; flood resilient building products and constructions (Golz *et al.* 2015). PLPs are increasing proposed and studied for their efficacy to prevent flood damage. The scope of this study includes: identifying the flood characteristics and damage impacts on a residential house during; and after a flood identifying the best types of supportive interventions which can help prevent water ingress as well as structural damage to the house.

The limitations to inform validity and use of findings are that: [1] Although, a local-scale approach is justified because the controversy surrounding integrated, large-scale damage projections (Cramer *et al.* 2014) demands a new "bottom-up" approach to account for the spatial and temporal heterogeneity that determines damages at the local-scale (Liu *et al.* 2015). The study is still limited by the building scale and its assumptions about its immediate surroundings. [2] The study focuses on flood prevention and excludes contamination damage, definition of flood repair measures as well as the quantity determination and valuation of such measures. [3] Lastly, economic or social dimensions of flooding are not covered.

2. Flood damage to buildings

Flood impact on buildings are often extensive and can be specified by the degree of experienced harm to their materials and structures and the deterioration of building functions (Blanco and Schanze 2012). Recent high intensity rainfall patterns have brought flooding concerns to many who never thought their homes would be flooded. People are underestimating the risks and hence little preparation and protection is being implemented (Fielding, 2008). In spite of the extensive research on flooding and the measures taken to achieve more resilient structures, a clear majority of existing construction techniques are still unsuitable for coping with flooding. It is therefore essential to work on flood prevention, by establishing a method of diagnosis of the vulnerability of buildings, and for determining the efficacy of property level interventions.

Research activity in flood damage assessments has rightly increased due to the rising prevalence and devastation caused by flooding globally. As a result, reliable models to estimate the flood damage are essential. The direct flood damage to buildings are typically estimated in two ways: [1] the analysis of the structural damage caused by the flood and, [2] The flood depth accumulated in the building. The structural damage is determined by the magnitude of the floodwater actions and the building materials resistance. The application of depth-damage functions (Pistrika *et al.,* 2014) typically aggregated in different ways in order to calculate flood damage to buildings is well established (Golz *et al.* 2015; Figure 2). Although it is also common to avoid the subject of structural damage altogether, by relating flood damage directly to the economic damage. However, focusing on flood depth as the main variable whilst in reality it is a complex phenomenon extremely simplifies the problem (Pistrika and Jonkman, 2010). In spite of this, flood depth is often considered as the exclusive determining factor of flood damage because logically the cost of repair works increases with the depth of floodwater (ODPM, 2003).

Flood characteristics as well as the economic/loss estimation approach used to assess flood damage are both useful for the design of flood mitigation techniques. But investigating the physical mechanism that causes the structural damage is more profitable for the future development of a flood-resilient property. Therefore, this study does not apply the depth-damage function, instead structural damage and the flood depth are examined individually relative to the flood characteristics. These analyses are interpreted against important building characteristics such as: building type; geometry, materials and; distance to flooding source (location within flood plains is considered a critical flood risk factor (Liu *et al*. 2015). The outputs are presented as degrees of water ingress and potential for structural damage (Types 1 and 2 in Figure 2). Also, the efficacy of specific flood prevention measures are explored.

Figure 2 Methodological steps for the synthetic calculation of flood damage to buildings (Naumann *et al.* 2009 in: Golz *et al.* 2015)

3. Causes and impact of flood damage

Flood damage can be divided into four types: direct tangible (e.g. physical damage due to contact with water), indirect tangible (e.g. loss of production and income), direct intangible (e.g. loss of life) and indirect intangible (e.g. trauma) (Jongman *et al.* 2012). The focus here is the direct tangible damage; structurally and through water ingress in to a residential building. The degree of structural damage depends on the intensity and magnitude of the flood actions (or loads), i.e. hydrostatic and hydrodynamic forces, and on the building's resistance to flooding (Kelman and Spence 2004; Pistrika and Jonkman 2010). For instance, damage may result from energy transfer, forces, or pressures leading to effects on buildings including wall failure, doors being forced open, glass breaking, roofs collapsing, or foundations being undermined.

Alternatively, the flood loss estimation approach is used to determine flood damage by: obtaining detailed flood parameters such as flow velocity, depth and duration at any given location; proper classification of damage categories considering nature of damage; and the establishment of relationships between flood parameters and damage for different damage categories (Dutta *et al.* 2003). When assessing and quantifying flood damage, priority is typically given to flood depth and repair costs based on the building material characteristics. Recent studies have however further established correlations between flood damage and flood characteristics (Soetanto and Proverbs, 2004, Kreibich *et al.*, 2009, Wagenaar, 2012). Finding that the rectification of the root causes can more effectively solve the problem. For instance, Kreibich *et al.*, (2009), focused on residential buildings and tested the effect of several parameters. Their findings summarised in Figure 3 found that water depth and energy head are highly correlated with structural damage.

Energy head is the total pressure from the Bernoulli Equation Indicator acting on the house and is the product of depth and velocity (Kreibich *et al.,* 2009; Figure 3). As the energy head is a parameter that describes both water depth and flow velocity, it appears to be a reliable parameter to forecast structural damage. However, energy head comprises of the pressure, kinetic and potential energy of the flow. The dominance of each of the three energies differ depending on the flooding scenario, all relating to the water depth. Potential energy dominates with high water depth, while kinetic energy dominates with low water depth (Kreibich *et al.,* 2009) and if the pressure is excessive compared to the strength of the wall construction, the extreme case would be the collapse of the house (Herbert, 2013). Also for static floods (slow moving water) the depth is considered to be sufficient for the analysis, but for dynamic floods, velocity is regarded as more important (Ciurean *et al.*, 2013). Therefore, this work focuses on other flooding characteristics e.g. flooding velocity and duration, rather than flood depth, to investigate structural damage and degree of water ingress.

Fig 3. Qualitative summary of the influence of impact parameters on flood damage (Kreibich *et al.,* 2009)

The velocity is strongly related to the distance between the house and the flood source, as well as the flood depth. Furthermore, an increase in velocity increases the tendency to wash out surrounding objects and transport quantities of solid matter. Therefore, the floodwater velocity also influences the probability of structural damage, if not necessarily the high structural damage (Soetanto and Proverbs, 2004).

Flood duration is also often ignored in flood damage models but it can have significant influence on the overall damage on a house (Wagenaar, 2012). The flood duration is highly correlated with the water depth – the longer the flood duration, the larger the damage caused to the building materials and the extent of flooding indoors (Wagenaar, 2012). This is especially important in the UK as many buildings are made of porous solid materials (e.g. bricks and blocks), meaning that the absorption of floodwater by the materials can contribute to subsequent to repair work (Soetanto and Proverbs, 2004). It is therefore beneficial to investigate all the above flood characteristics alongside with the building material characteristics to give the final flood damage.

3.1. Flood Damage Modelling

Recent studies have focussed on addressing the limited knowledge about the physical causes of flood damage beyond the description of flood depth and associated characteristics (Kelman and Spence 2004). As a guide, de Moel and Aerts (2011), building on the work of Meyer and Messner (2005) and Messner *et al.* (2007) stated that flood damage assessments are underpinned by four components: [1] hydrological characteristics, mostly represented by flood depth; [2] elements at risk, often estimated using land use or individual buildings; [3] value of elements at risk and; [4] susceptibility of the elements at risk to the hydrological characteristics, usually defined using depth–damage curves.

Thus, modelling methods have evolved to accommodate more comprehensive consideration of flood damage factors. For example: Liu *et al.* (2015) utilised historical data series to study the relationship between disaster loss and flood risk factors, then investigated future losses based on three factors – hazards, exposure and vulnerability. Zhai *et al.* (2005) accounted for the house type and length of residence while Wind *et al.* (1999) included flood warning time. Meanwhile, Dutta *et al.* (2003) argued for the integration of the distributed hydrologic and loss estimation approach. Their study used the physically based hydrologic model consisting of major hydrologic processes and the governing equations for flow propagation in these processes which were solved using finite difference schemes. Whilst the loss estimation model, based on the unit loss approach, consisted of three kinds of primary tangible flood damage: urban, rural and infrastructure damage.

Assessment of flood damage using modelling have also been conducted at the micro, meso (catchment) and macro urban scales. Work at the macro and meso scales include Apel *et al.* (2004); Kourgialas and Karatzas (2013) and, de Moel (2011). Whilst others like (Kreibich *et al.,* 2009) have focused on the micro scale. Also, modelling methods have used historic and/or real-time data to underpin predictions and outcomes.

From literature, it can be established that flood damage modelling methods and methodology vary depending on the scale, scope, purpose and application. Wagenaar *et al.* (2015) found significantly different results when modelling is applied to the same events. Citing the works of De Moel and Aerts (2011); Jongman et al., (2012) and Chatterton et al. (2014), they found differences between the smallest and largest estimate/recording in the outcomes of seven different flood damage models based on recorded flood damages events in the UK and Germany. Difference by a factor 5 for the German event and a factor 10 for the event in the UK. In examining two different damage assessments for a region in the UK, the damage estimates differed by about a factor 5 to 6 for both residential and commercial damages. These large differences indicate that flood damage models are prone to large uncertainties (Wagenaar *et al.* 2015).

The estimation of direct flood damage (focus of this study) is therefore a complex process involving a large number of hydrologic, building and socioeconomic factors, and several degrees of uncertainties in datasets. Therefore, the structure, inputs and outputs of a specific damage model should be defined and interpreted not only by the available data, *but also by the purpose of the model* (Jongman *et al.* 2012). To this end, flood damage models remain beneficial to support stakeholders to make crucial decisions about flood mitigation measures and investments.

3.2. Effect of floodwater on materials

The effects created during a flood event can significantly damage the materials of building components even though many building components are designed to withstand rain and moisture contact (PCA, 2015). Damage could occur especially when these materials are submerged and have prolonged duration of water contact. Masonry, timber and concrete are three common structural building materials used in residential construction according to the

UK's Construction Building materials Bulletin 2016 with flood performance summarised below:

- **Timber:** Timber is commonly used in residential buildings: for timber frame, partition walls, as well as flooring. During and after a flood, the wood will be soaked with floodwater and have a slow overall drying process (CIRIA, 2007). The timber flooring will suffer the most as it can be fully submerged in floodwater and cause damage to the building when it absorbs water, swells and buckles (Preston-Strout, 2012). In 2006, researchers at the University of Cambridge (2006) conducted studies to find out the effect on the mechanical behaviour of wood by water. By soaking wood in water for 24 hours, they found that the increase in water content of wood lowers the stiffness and strength. Compressive strength of some species of wood can become as low as 20MPa, from the original 70MPa.
- **Concrete:** Concrete has low permeability and is well known for its compressive strength. Concrete experiences minimal damage by floodwater and is perfect as a flood proof material compared to other materials (The Concrete Centre, n.d.). A trend of using concrete as a construction material to build structures near watercourses has been observed. In recent years, floating houses are built with concrete, having the idea of raising the level of the house with the increased water level during a flood (Winston, 2014).
- **Masonry:** This material is selected for primary study because according to the Traditional Housing Bureau, 70% of new homes that are built in the UK still use the traditional masonry construction method (The Self Build Guide, 2015). The brick and block wall will therefore be the first building component that come in contact with the floodwater.

Therefore, this study focuses masonry. Following the masonry design manual (BS EN 1996-1-1), a uniformed lateral load representing the wind load is assumed during the design. As water pressure distribution is triangular, and increases with depth, it is necessary to consider the strength of the wall accordingly. A previous experimental work by Herbert (2013) investigated the effect of hydraulic lateral loading on different masonry units and compared the results to the uniform wind lateral loading. It was found that the specimens failed more rapidly with hydraulic loading than wind loading. The failure can be described as no warning and abrupt. Furthermore, the maximum water depth before failure is 0.24m for a single leaf specimen wall. Whilst the tested specimen was limited and the floodwater had no direct influence on the material properties of masonry, the water depth that is safe for a masonry wall to withstand is definitely not high before failure (Herbert, 2013).

3.3. Flooding interventions

Floodwater can potentially cause damage to both the exterior and interior of house. Depending on the duration of the flood, the water contact time with the materials and volume of water entering the building differs. Floodwater will follow a path of least resistance and enter at the weakest points in construction. In order to find out how to protect the house, the floodwater pathway for entering a house that could potentially result in damage should be identified (Figure 4).

Fig 4. Possible pathways for ingress of floodwater (CIRIA, 2007)

It is critical that houses built or to be built on a floodplain are retrofitted or designed appropriately to cope with floodwater. However the lack of building regulations that address the resilience of new or existing developments to flooding, has resulted in no effective market for flood resilient property (Garvin, 2016). It is therefore common for house occupants/owners to mainly use sandbags for flood protection. This measure can however be ineffective and still leaves costly repairs. Fortunately, the deficiencies of the flood defence available in the market have been improved with better protection techniques (EA, 2012).

HR Wallingford is nominated by the British Standards Institution as the national laboratory for the assessments, where models and best practices which are most effective for keeping floodwater out can be found (ABI, 2016). All tests are done using large scale physical models in controlled laboratory settings, to evaluate the water tightness of the interventions. They follow the Flood Protection Products Specification (*PAS 1188-1:2014*), which specify the accuracy range of the typical test conditions that can be experienced during a flood as:

- 0.54m – 0.84m static water levels (depends on the specific leakage test)
- Waves up to 0.1m high
- Parallel current velocity up to 1m/s.

The interventions with successful test outcomes are recognised with the BSI Kitemark certificate. BSI Kitemark scheme is supported by the Environment Agency and interventions bearing the mark are proven to be fit for purpose (BSI, 2016). These interventions do not necessarily alter the way a building is designed and can be applied to any house. These PLPs all about applying the measures that could protect houses from flooding through resistance and resilience measures (EA, 2012).

- **Resistance measures:** Resistance is “constructing a building in such a way to prevent floodwater entering the building and damaging its fabric” (CIRIA, 2007). Resistance measures consist of products such as barriers, floodgates, airbrick covers, and non-return valves etc., which can be fitted quickly onto the exterior of the house to prevent the ingression of floodwater during a flood event (JBA Consulting, 2014). It is impossible to flood-proof or seal a house completely and none of the interventions are infinitely good at stopping the ingress of floodwater, therefore it needs to be accepted that floodwater may still get in even with the resistance measures applied (ABI, 2016).
- **Resilience measures:** For longer duration, intensive flooding, floodwater may overcome the resistance measures. In this scenario, making the house more resilient is important. Property owners can utilise resilient materials and design, allowing the house to return to a habitable state quicker. Resilience measure is “constructing a building in such a way that although floodwater may enter the building, its impact is reduced” (CIRIA, 2007). Resilience measures include material choices, such as waterproof plaster, tiled flooring etc. Raising power sockets and furniture, installing pumps and mortar joints sealing are also part of resiliency (JBA Consulting, 2014).

To apply multiple interventions at the same time appears to be a good idea but, this may be counter-productive. But building codes can offer disparate guidelines on the recommended sealing height (BSI, 2005). Take mortar sealing of a masonry wall as an example, a research by Pace (1988) studied the collapse load on full-scale sealed masonry walls and concluded that sealing of the wall should not be greater than 0.9m (3ft). Note that the research is based on construction techniques used in America and factors such as vertical imposed loads from multiple storey construction are not considered. Based on this study, the UK guidance became that the sealing height should not exceed 0.9m to avoid structural damage but gives no justification (ODPM, 2003; BSI, 2005). Since then, the UK guidance reduced the sealing height to 0.6m and Pace's research was directly referenced (CIRIA, 2007; PCA, 2015; Garvin, 2016); stating that if the flood depth is likely to increase above 0.6m, water should be allowed to enter the property at a safe flow rate. Although the reduction from 0.9m to 0.6m is probably due to safety factors, these guidance appears to contradict the findings by Pace. Table 1 summarises the designated maximum water depth of the three leakage tests published in the previous Flood Protection Products Specification (*PAS 1188:2009)* and the current version (*PAS 1188:2014).* The new version shows an increase in the maximum height. However, of the materials currently available, the Flood Protection Products Specification appears to be the most technical piece of work, providing the procedure for testing the interventions.

Table (1) Designated maximum water depth on the leakage tests

4. Methodology

Flood risk analysis can be undertaken using three broad approaches: risk analysis, hazard analysis and/or vulnerability analysis (Apel *et al.* 2009; Merz and Thieken 2004): Risk-oriented methods and analysis help to quantify risks and evaluate cost-effectiveness of mitigation measures to optimise investments; Hazard analyses give an estimation of the extent and intensity of flood scenarios and associated exceedance probability to it and; Vulnerability analyses estimates the detrimental effects caused by the floodwater such as fatalities, financial and economic losses and building damage. Vulnerability analyses of building-specific damage functions can be undertaken using two approaches: collecting flood loss data in the aftermath of a flood or "what-if analyses" (ex-ante analysis), by which the damage which is expected in case of a certain flood scenario is estimated, e.g. "What damage would you expect if the water depth was 2 m above the building floor?" (Apel *et al.* 2009).

In this study, What-if, scenario-based vulnerability analysis is used to answer broader questions highlighted through literature review as follows: What are the effective intervention(s) that can help deliver resilience to houses? Which part of the house is more vulnerable and need protection? How far away from the water source should the house be built to reduce impact? Would the orientation of the house affect the total impact?

To answer the research questions, modelling and simulation tools were employed to test the specified flood inundation parameters and scenarios (Dutta *et al.* 2003; Kourgialas and Karatzas 2013) of a typical detached house. The model allows accurate input of values, which means that the results obtained will match the considered scenarios based on standard equations and assumptions made – *the idealized model*. Although the validity of mathematical approach concerned with developing normative models in describing the real world complex phenomena and the predictive capability can be weak, it provides the first vision and an objective basis to explore the questions under study.

4.1 Research design and approach

This research design focused on methods necessary to investigate and understand:

1. Floodwater impact on a detached house based on the distance between the house and the flood source, orientation of the house, velocity of flow and flood depth
2. Current common interventions to prevent the ingress of floodwater

The research was proposed in two parts. The first part explored the effect of distance, orientation and velocity on the damage of a house using the following steps:

1. Model a house to sufficient details in a water domain
2. Flood the house and measure the structural damage
3. Change the distance between the water source and the house and repeat the test
4. Change the orientation of the house and repeat the test
5. Change the flow velocity and repeat the test
6. Discuss the findings of the effect of altering the distance, orientation and velocity.

The second stage of the study explored only the worst orientation in detail so that the consequence of applying an intervention can be shown. One of the study's hypothesis was that the closer the house is to the flood source, the higher the degree of flooding and the structural damage. As houses are increasingly being built near water, a range of distances were applied to find the distance where the interventions can have the most significant impact. A suitable velocity was chosen based on the results obtained.

The second part thus investigated the performance of each intervention using the following steps:

1. Model the interventions
2. Apply interventions one at a time and repeat the test

After finding a suitable position and orientation for the house in the model, each chosen interventions was applied to test their effectiveness. The performance of the interventions and the most effective intervention for keeping floodwater out were found. It is worth mentioning that the flood duration in this second part was set as two hours. This is to adequately reproduce a flash flood scenario, while allowing enough time for the floodwater to establish its flow. This in effect gave suitable conditions for testing the interventions.

4.2 Research methods

Methods included a review of existing literature as well as the following:

- **Desk review:** Various PLP interventions were researched online from a range of companies including those commonly listed on product archives. Table 2 shows a comparison of the selected interventions and products.

Table 2. Interventions to be investigated

- **Empirical study:** A detached house was modelled in 3-Dimension in AutoCAD and imported into ANSYS Fluent® from the ANSYS workbench. ANSYS Fluent® is a CFD tool that can predict fluid flow by solving a set of mathematical equations, including conservation of mass, momentum and energy. The software uses its built-in monitored data and solves equations iteratively until convergence is found. In the case of this study, Fluent® can predict the water flow; the energy of the flow damaging the house; as well as the accumulation of water in terms of time and quantity. In terms of reproducing a flood scenario, a 'tank' approach was used. A shallow infinite tank relative to the position of the house was modelled, and water level increased until the house is submerged to achieve a simulated a flood event.

4.3 Model Setup

A simple **solid wall** house was first used to test the flood impact based on different distances, orientations and velocities. The premise was that pressure and shear acted on the external wall will not change significantly if it is solid or of cavity construction. Further, initially testing a solid wall house sped up the meshing process as well as the program running time.

The model's plan area was 88.75sqm with dimensions as shown in Figure 5a. It was then placed in the fluid domain at the different modelled positions. The domain was designed to model a river that cannot convey the excess water and so overtop the river bank onto the dry land adjacent to it. The back of the tank was set as an 'outlet', to enable water to continue to flow inland rather than accumulate.

Fig 5a. House model dimensions and house in fluid domain

Figure 5b. Cavity house used for the interventions analysis (material specification and parameter absorption coefficient applied in ANSYS Fluent®)

Fig 5c. Plan view of the hollow house

For testing the interventions, a **cavity** wall section with 102.5mm thick walls was then used. A flood duration of two hours was used to represent the flash flood scenario and to ensure sufficient water had entered the house. Front and back door gap, old masonry gaps, pipe holes were placed in typical positions of the house (Figure 5b and 5c).

The data and assumptions in the model are shown in Table 3, only considering the damage caused by the direct contact and ingress of floodwater into the building.

Table 3. Summary of the assumptions applied to the model

ANSYS Fluent® provided many monitored data throughout the test. All tests were ran under the 'Transient' function, which means that data can be collected over a specified time frame. This way, the exact time of floodwater reaching the house and when the water started to seep through in the house can be observed. Calculated values like pressure acting on the walls obtained from the program further aided the investigation. ANSYS Fluent® can also locate where the maximum pressure is at that time frame selected with the use of coordinates. This showed which part of the house is more vulnerable. The maximum pressure data was also used to calculate the shear stress acting on the wall as follows:

$$Maximum\ shear\ stress = \frac{Pressure \times length\ of\ wall \times 1}{3}$$

The tests commenced with an assessment of the pressure and shear force that can be safely borne by a masonry brick and block structure. Supposing the cavity wall structure of: 102.5mm clay brick outer leaf, 150mm mineral wool and 100mm aggregate block inner leaf. The clay bricks use a M6 mortar with water absorption between 7-12% and the aggregate blocks has a compressive strength of 7.3N/mm^2. Following the *BS EN 1996-1-1* masonry design manual, the design lateral load per unit area for the longest span wall (11m) would be **5.4kPa** and a shear strength of **197kPa** (Table 4).

Table 4. 11m brick and block masonry wall calculation

As well as the calculated values, the software allows colour contour maps showing specified variables. The most applicable variable is the 'volume fraction', which shows the volume of water moving in the domain with time as a fraction in a rainbow colour plot – *red* representing the highest fraction of water and *blue* representing the lowest fraction of water. For example, Figure 6a shows the default colour scale and the results to be presented in Section 5 will be based on this colour scale.

4.4 Assumptions, Exceptions and Limitations

ANSYS Fluent® setting assumptions were as follows: A pressure based solver was used as it is applicable for a broad range of flow regimes from low speed incompressible flow to high speed compressible flow. The Transient analysis was used to monitor the flow regimes at certain time period. Materials used in the model is the default settings of air and water (liquid) defined by ANSYS Fluent® material database. It was assumed that there will be no heat transfer in the liquid, with a constant water temperature of 15˚C. Standard initialization is used. The iteration values for the model were computed using the inlet boundary condition – 0.5m/s. Although the initial values would not directly affect the results but suitable values should allow the calculations to run smoothly. 'Green-Gauss Node Based' and 'First-Order Upwind' schemes settings are used as it minimises false diffusion and give greater accuracy as well as quick convergence respectively. The 'Under-relaxation factors' were unchanged unless the convergence residuals are not reaching the desire level – below 0.001.

Exceptions are as follows: Any flooding caused from internal sources, for example bursting of pipes or problems caused by leakage of roof were excluded from the scope of the research. Any seepage from the ground and moisture through the walls are also not considered. As none of the building content were modelled, some of the resilience measures like raising sockets and furniture are not investigated. The ground of the model was set to be flat, so there is no gravitational effect on the flow of water. The effects of the presence of other surrounding obstructions e.g. other houses are not considered under the modelling process, hence the flow in contact with the house will experience no drag and have no transport of solid matter. Also, there will be minimal turbulence of the flow due to no surrounding obstructions.

It would be ideal to analyse a more detailed house model which included the soil and foundation as well as the structure itself. However, this additional complexity would not have added value as the only focus of this study was direct structural flood damage. It was therefore sufficient only to model the structure of the house above ground level. Also, the model does not represent the real construction of the house, for example, the defects caused by workmanship and in materials cannot be modelled easily. Each individual house would experience a different impact from the flood depending on the shape, size, orientation and distance to the flood source. It is therefore impossible to model every single house in their unique conditions. As the model is set up with no adjacent properties and no specific geography, the results will only be very generic, not suitable to apply to all flood scenarios.

The accuracy of the solution is dependent upon the appropriateness of the physical model, the mesh quality and numerical errors. The mesh quality and numerical solutions are carefully monitored, ensuring the conservation equations are fulfilled. Providing the simplification of the model is representable of the real life scenarios, the results obtained should be true with the assumptions made above.

5. Modelling Results

5.1. Independent variables

Results associated with the independent variables pertaining to the distance to a water body, orientation of the building etc. are discussed as follows:

5.1.1 Distance

For this analysis, the house is placed in the middle of the domain and at various distances from the river. The test is performed from 0m to 50m, with an interval of 5m. Presence of obstructions such as trees, surrounding buildings and infrastructure in real life are not considered.

A sensible estimate of 1m/s (same as *PAS 1188-1:2014*) was used for the water flow velocity. The first ten minutes was simulated and it was found that the water had fully established around the house even in the furthest distance (50m). Figure 6a shows a colour scale from red to blue of the water volume fraction after 600s of the 50m distance, with red showing the highest fraction of water.

As the house was placed at a range of distances, the times for the water to reach the house were different. To conduct a fair analysis, comparisons were then made on the data only after the water has reached the house. Figure 6b show the time taken for the water to reach the house and the time for the peak average pressure to act on the house. The two lines are linear and relatively parallel. This shows that the time taken to establish the flow around the house is the same for all distances, which is approximately 130s.

Fig 6a. House placed at 50m after 600s of simulation

Fig 6b. Time taken for the water to reach the house and the time for the peak average pressure to act on the house

For the ten minute simulation, it took 160s for the flood water to reach the house at 50m, meaning that the house was in contact with water for 440s. Accordingly, data was collected 440s after the water had reached the house for each distance and Figure 7 shows the

average pressure. As expected, the closer the house is to the flood source, the higher the pressure acted on the house. Towards 30m, the pressure plateaued and is almost constant.

Fig7. Average pressure after 440s

The **average** pressure around the house showed a clear relationship between the pressure acting on the house and the distance away from the flood source, and was well under the safe lateral load. However the water level around the house was not evenly distributed, the front of the house has a higher water level before a full establishment of water around the house. The following table presents the maximum pressure acting on the house.

Table 5. Measured results by changing the distance (flood height for reference only)

The maximum pressure at the front of the house clearly exceeded the safe design value but was safe in shear. Unlike the average pressure, the magnitudes showed no trend in the maximum pressure results. The maximum pressure did not decrease with the increase in distance. Although the reason for this is yet to be fully explored, it is likely caused by the nature sine/cosine wave propagation. This means that the water particle reached its highest level in the cycle, resulting in higher pressure at 15m, 30m and 50m despite being far away from the source. The height of the water also reached the second storey of the house which does not accurately reflect a simple real life scenarios.

5.1.2 Orientation

The flood impact to the house will differ, depending on how the house is positioned relative to the flood source. The tested orientations of the house relative to the watercourse e.g. river are as shown in Figure 8. Under the same condition, it was found that the 315˚ orientation experienced the highest pressure and the 135˚ orientation experienced the least pressure (Table 5).

Fig 8. Plan view of house orientation placed in front of the river

Table 6. Measured results by changing the orientation (flood height for reference only)

The tests stimulated the first five minutes of the flood event with a flow velocity of 1m/s. As the houses are placed right beside the river, the pressure acting on the house all exceeded the design lateral load. The position of where the maximum height of water depended on the surface area of the wall facing the river and the position of the 'L' shape relative to the river. The 90˚ and 180˚ orientations have a large surface area facing the river, hence the maximum water height is at the front of the house. Other orientations mainly accumulated water in the 'L' shape.

The 315˚ orientation was found to have the highest pressure acting on the wall because the water accumulated in the 'L' shape of the house, and the position of the 'L' shape relative to the river made it hard for the water to dissipate away. The 135˚ orientation had the lowest pressure conversely, but two peak pressure were found. The water first accumulated at the front of the house, then in the 'L' shape later on (number in the bracket in Table 6). The height of water accumulating in the 'L' shape were also significant and could potentially reach the second storey for both orientations (Figure 9). Even though the height of water for 135˚ is comparable with the other orientations, the pressure was not as high as the other scenarios due to the high velocity head formed by the streamlined 'V' shape front facing wall, reducing the overall structural damage.

Fig 9. Maximum height of water relative to the house. Left to right: front of house 315˚ at 140s, back of house 135˚ at 180s

5.1.3 Velocity

From the previous two datasets, it was apparent that the flow velocity can generate a high pressure on the walls which exceeds the design lateral load. In this section, the effect of flow velocity is investigated and a linear relationship was found between velocity and pressure (Table 7).

Table 7. Measured data by changing the flow velocity (flood height for reference only)

The findings suggest that increasing the 'unobstructed' distance between the river and the house would not greatly change the pressure acting on the house as a result of the flood, but it is worth testing that a drop in velocity could potentially give a change in pressure with distance.

All distances and orientations were tested with 1m/s flow velocity, and all scenarios showed high pressure acting on the house wall. This simply suggests that brick and block masonry walls are not ideal for housing built near a water body. Instead, concrete walls, at least at the lower levels, should be considered for houses on floodplains. On the other hand, the shear stress never exceeded the shear strength of the masonry wall. Therefore, the lateral shear strength may not be the main concern when designing a masonry wall to resist the water pressure.

Next, the shortlisted PLPs were investigated using the following parameters: distance of 20m and 30m, 315˚ orientation and 0.5m/s flow velocity. Distances less than 20m were not be tested due to its rareness and the almost overtopping height of water accumulation. After 30m, the structural damage was found to be almost constant, so distances after this were also not tested. A flow velocity of 0.5m/s was used to allow sufficient water ingress to show the significance of applying any of the interventions.

6. Results

Before any interventions were applied, the house was tested with all possible water ingress pathways (see Figure 5b) to establish the baseline. The degree of flooding ingress indoors and structural damage were measured and presented through contour maps showing water volume fraction in the house and the pressure applied on the walls. Testing with a distance of 20m and 30m, an orientation of 315˚ and flow velocity of 0.5m/s, Figure 10 shows the plan view of water distribution in the house. It can be observed that the water ingress did not occur through the gaps until the height of water outside the house was approximately 0.3m. This supports the findings of Liu *et al.* (2015) which showed that damage climbs as the volume of water increases. They further found that the degree of damage gradually flattens out as the realized damage approaches a maximum value of damaged assets.

Fig 10. Contour map of water distribution on the floor after two hours of flooding with no intervention

Unsurprisingly, the 20m distance showed more water entering into the house. There were areas of high water levels and low water levels. This result is interesting as it is common to predict that the water level indoors will be evenly distributed. However, the results appear to suggest that water generally accumulates on the right hand side and the indoor water movement appears to be circulating. One suggestion for why the water level on the left hand side was generally lower is that the front door gap is larger compared to the others, which allows more ingress as well as outflow of water. The area of low water level is observed to take a circular shape, which suggest that the water forms vortexes of lower water levels as it circulates within the house. This behaviour is typically not observed because of the tendency to have furniture and obstructions in the house in real-life flood scenarios, making the movement of water less energetic with drag and friction, hence an even water level is generally perceived.

The maximum pressure around the house for the distance of 20m and 30m were 23.6kPa and 21.3kPa respectively. Compared with the ‘solid’ house tested in the previous section, the pressure on the ‘hollow’ wall house has reduced even though this orientation is expected to accumulate water with high pressure generation. This supports the resilience approach of letting floodwater through/into the house rather than resisting/stopping the flow when the water accumulates. This is effective for reducing structural damage as suggested by Pace (1988)’s research.

Referring back to the velocity test in the previous section, Table 8 shows a comparison of the maximum pressure with the three distances. Again, there is no pattern in the relationship of distance and maximum pressure.

Table 8. Maximum pressure with flow velocity of 0.5m/s

Table 9a summarises the maximum pressures after the interventions. Table 9b shows the contour plots and maximum pressure on the house when different interventions were applied based on flooding for two hours.

Table 9a. Summary maximum pressure after applying interventions

Table 9b. Results summary of applied interventions

Table 9b summarises the maximum pressure acting on the exterior of the house walls when different interventions are applied. Notably, the pressure is highest when no interventions are applied. This means that all interventions contributed to reducing the structural damage to the house. Repeatedly, the pressure did not vary with the change in distance to the flooding source. The random nature of the findings however indicate that no conclusions can be deduced without further investigation. When non-return valves were applied to the 20m house, the pressure was comparable to the pressure with no interventions. The degree of indoor flooding reduced by applying the non-return valves was also insignificant. For these reasons, non-return valves are not recommended for the 20m house. The best option appears to be to apply two floodgates. They effectively stopped the water ingress into the house, leaving minimal surface water indoors. Although the pressure had slightly increased from having only one floodgates, this remained within acceptable limits and the minimal water ingress was also considered beneficial. On the other hand, having one floodgate appeared to be a better option for a 30m house. Despite the fact that one floodgate could not give the optimal effect of stopping the water ingress, the pressure doubled by applying the second floodgate, which could be structurally detrimental.

Mortar sealing at 0.6m reduced the maximum pressure which supported Pace's study that the maximum sealing height should be 0.9m instead of 0.6m. All the above suggestions are based upon having a wall construction that would not collapse under the maximum pressure. Mortar sealing at 0.6m reduced the maximum pressure. The effect of mortar sealing is however not as compelling as the results from installing floodgates. However, note that in this research, the old masonry gaps are represented as two big holes rather than allowing water through at various small unfilled mortar gaps. Timber flooring is a popular flooring option that has stood the test of time. However as discussed in the literature review, timber is vulnerable when in contact with water. To avoid the timber damage, concrete is strongly proposed as a replacement material. The parameter absorption coefficient was used to assess the resistivity of materials in ANSYS Fluent®. Timber was set to a value of one as default and concrete has been set to zero for maximum comparisons. Looking closely at the contour map, there are areas that appear to have more water present for the concrete flooring. Figure 11 shows a sample result for the 20m house. The top corner of the house has higher volume fraction of water in the house with concrete flooring. This suggests that the timber has indeed absorbed some water, leading to a lower water volume fraction, but damaging the material itself.

Fig11. Zoomed in contour map for a 20m house after two hours of flooding. Left to right: timber floor, concrete floor

7 Discussion

The findings show that distance from the flooding source, the pressure of flood water, the form and orientation of the house all contribute to varying degrees to the degree of structural impact and consequential water ingress in the modelled 'idealised' masonry detached house. However, no linear variations were found between pressure and distance and closer proximity to the water source increased the propensity for water ingress. The green area of the colour contour maps represents approximately 0.3m of water and the water outdoors was found to be higher than 0.3m. This means that the flood water levels indoors and outdoors are not in equilibrium after two hours of flooding. This confirms what was detailed in CIRIA (2007) about the time lag in water ingress as shown in Figure 12.

Figure 12. Conceptual illustration of flood water depths outside and inside a building with time (CIRIA, 2007)

Notably, it was found that the pressure on the structure is highest when no interventions are applied. This means that all interventions contributed to reducing the structural damage to the house. Repeatedly, the pressure does not differ with the change in distance.

The efficacy of a number of PLPs to reduce or minimise the ingress of water into the house as well as their effect on the pressure acting on the external house wall was then investigated. The pressure in general decreased with any intervention applied, suggesting that some benefit could be derived from their installation. However, it was also found that there were increased risks of structural damage with some interventions, therefore caution should be applied and professionals consulted before their use. For instance, floodgates give the best performance in stopping the ingress but having two would increase the pressure acting on the house walls. Non-return valves are not advisable for the 20m house due to the high pressure and the negligible effect on reducing the water ingress. When non-return valves were applied to the 20m house, the pressure is comparable to that recorded when no interventions were applied. The reduction on the degree of flooding indoors by applying the non-return valves was also outstanding. The model was set up with the expectation that the two pipe holes can act as outlets in the house, releasing water back to the outdoors. However, due to the higher pressure of water outside the house, it effectively stopped the ingress of water through the pipes whilst not allowing any outflow. For these reasons, non-return valves may not be ideal for the 20m house but this may be mitigated by pumping the flood water back outdoors. The two floodgates appeared to effectively stop the water coming into the house, leaving the minimal surface water on the floor. But, the pressure on the structure slightly increased from having only one floodgate, so the benefit of little standing water in the house against the extra structural load should be considered. On the other hand, having one floodgate may be a better option for the 30m house with the specified orientation. Despite the fact that one floodgate could not give the optimal effect of stopping the water ingress, the pressure doubled by applying the second floodgate, which again could be detrimental to the structure.

Airbricks were not modelled in detail due to the granularity of the idealised model. Due to their position, they could however allow up to 50,000 litres of water if no protection is installed. The airbrick cover, could therefore theoretically stop the ingress of water beneath the floor, providing that the masonry wall is adequately sealed. This greatly reduces the water contact with the floor and also avoids the trapping of moisture underneath the floor level as those areas are very troublesome to dry out.

To summarise, the pressure does not linearly vary with distances and there is more water ingress for the 20m house after two hours of flooding. Floodgates give the best performance in stopping the ingress but having two would increase the pressure acting on the house walls. Non-return valves are not advisable for the 20m house due to the high pressure and the negligible effect on reducing the water ingress. The validity of all the above suggestions are based upon having a wall construction that would not collapse under the maximum pressure and this specific house typology and design.

7. Conclusion

The flooding awareness and action taken by citizens is increasing recognised as important for collective resilience. However, studies repeatedly show low levels of awareness, anticipation and adaptive capacity in flood risk areas. Where actions have been taken, disparate property-level solutions were implemented without full understanding of their degree of effectiveness or impact on the building's structural integrity. This study addresses this gap in a simple manner with concise outputs that provides a theoretical approach for examining appropriate and effect flood resistance and resilience interventions without adverse effects on the building's structure. In this study, existing building standards for structural impact of flooding are evaluated and it was found that parameters such as building form, flow velocity impact on the extent to which minimum building guidelines and standards apply.

Specifically, the findings build on the current knowledge of flood damage to make a contribution to the understanding of the vulnerability of the chosen housing typology to structural damage and water ingress. The potential for uncertainties and differences in outcomes of flood-damage models were also discussed. It affirmed that inundation depth is not the only useful hazard indicator that contributes to the quantity of losses. The importance of other influencing factors like flood velocity and duration of inundation are emphasized.

The main findings pertaining to the impact of floodwater in terms of the distance between the house and the flood source, orientation of the house, velocity of flow and flood depth can be summarised as:

- The average pressure shows a decreasing trend with increased distance from the flood source.
- The maximum pressure acting on the house does not show any relationship with the distance away from the flood source, even with different flow velocities.
- Concave corners are detrimental as it allows accumulation of water there, hence increase the possibilities of structural damage.
- Streamlined shape can effectively reduce the structural damage of the house, although not the depth of the water.
- Flow velocities has a huge impact on the pressure acting on the house when very near to the flood source.
- Ingress of water into the house only started when approximately 0.3m of water height is outside.
- The maximum pressure data collected with the stated boundary conditions have all exceed the strength limit of the wall construction.

Following these findings, the effectiveness of the investigated property-level interventions are summarised as:

- Floodgates show the best performance, reducing the exterior pressure while also reducing the water level indoor.
- However applying two floodgates, one for front door and another for back door, resulted in a significant increase in pressure.
- Non-return valves shows an overall reduction in water ingress, but the increase in pressure might not be beneficial.
- Mortar sealing still shows a positive effect in reducing the pressure and indoor water level at a sealing level of 0.6m, confirming current guidelines.
- Airbrick covers should be used to prevent the huge influx of floodwater underneath the floor level.

With the typical brick and block masonry wall, ANSYS Fluent® analyses show that the pressure on the solid house walls by the floodwater was highly significant. Therefore, this wall construction is not advisable in flood risk areas. Concave corners should be avoided, instead simple rectangular shape work better for avoiding the accumulation of water. Other shapes like circular and streamlined shape (such as a 135° orientation) are also feasible. A balance between the degree of indoor flooding and the structural damage is found to be the best practice. All above findings should only be applied in conjunction with the specific house design tested scenarios and assumptions made in this study; including the lack of obstruction between the watercourse and the house. Still, these findings are highly useful for property owners, managers and developers to aid flood resilience decisions, investments and actions.

Future work will further investigate the significance accumulation of flood water high up the external walls, related to the flood depth in the models. The efficacy of combined or integrated PPL interventions will be studied. There is also scope to investigate other building materials such timber and concrete in more detail, or the combined use of materials in housing construction. Lastly, further methodological contributions could be made by investigating the use of tools such as ANSYS Fluent® or similar, to improve the current understanding of flood impact on buildings.

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Table 1. Designated maximum water depth on the leakage tests

	PAS 1188-1:2009 (BSI, 2009)	PAS 1188-1:2014 (BSI, 2014)
Static head leakage test	0.60m	0.84m
Wave leakage test	0.45m	0.54m
Current leakage test	0.50m	0.74m

Table 2. Interventions to be investigated

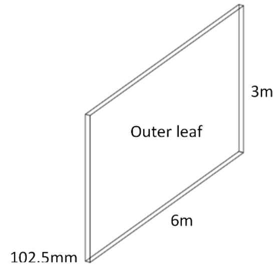
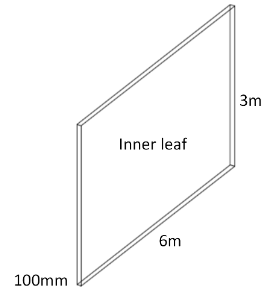
House component	Intervention	Type of measure
Door	Floodgate	Resistance
Airbrick	Airbrick cover	Resistance
Drainage	Non-return valve	Resistance
Wall	Mortar sealing	Resistance / Resilience
Floor	Flood proof materials	Resilience

Left to right: floodgate, airbrick cover, non-return valve (UKFDA, 2017)

Table 3. Summary of the assumptions applied to the model

House model	Comment
2 stories house, 6m in height	
200m x 70m x 7m fluid domain	
Approximately 88sqm plan area	Average three bedroom home (RIBA, 2011)
2 x 12mm x 2100mm door gap	Front and back door gap
2 x 200mm x 70mm old masonry gap	Defects in the masonry wall at 0.6m height
2 x 100mm diameter pipe holes	Typical plastic pipes dimension for household drainage
Flood duration set as 2 hours	Flash flood area
Floor material: timber, concrete	Two typical materials used for flooring

Table 4. 11m brick and block masonry wall calculation

		
$\boldsymbol{f_{xk1}\ (N/mm^2)}$	$\mathbf{0.4}$	$\mathbf{0.25}$
$\boldsymbol{f_{xk2}\ (N/mm^2)}$	$\mathbf{1.1}$	$\mathbf{0.6}$
$\boldsymbol{f_{vk0}\ (N/mm^2)}$	$\mathbf{0.2}$	$\mathbf{0.15}$
$\sigma_d = unit\ weight \times total\ height \times 1.5$ $\boldsymbol{(N/mm^2)}$	$20 \times 10^{-6} \times 6000 \times 1.5$ $= \mathbf{0.18}$	$19.5 \times 10^{-6} \times 6000 \times 1.5$ $= \mathbf{0.176}$
$\boldsymbol{\mu = \frac{f_{xk1}}{f_{xk2}}}$	$\mathbf{\frac{0.4}{1.1} = 0.36}$	$\mathbf{\frac{0.25}{0.6} = 0.42}$
$\boldsymbol{h/l}$	$\mathbf{\frac{3}{11} = 0.27}$	$\mathbf{\frac{3}{11} = 0.27}$
$\boldsymbol{Condition\ I: \alpha}$	$\mathbf{0.009}$	$\mathbf{0.008}$
$\boldsymbol{\gamma_M}$	$\mathbf{3}$	$\mathbf{3}$
$Z = \frac{bd^2}{6}$ $\boldsymbol{(mm^3/m\ height)}$	$\frac{3000 \times 102.5^2}{6}$ $\mathbf{= 5.25 \times 10^6}$	$\frac{3000 \times 100^2}{6}$ $\mathbf{= 5 \times 10^6}$
$M_{Rd} = \frac{f_{xk2}}{\gamma_M} Z$ $(kNm/m\ height)$	$\frac{1.1}{3} \times 5.25 \times 10^6$ $= \mathbf{1.93}$	$\frac{0.6}{3} \times 5 \times 10^6$ $= \mathbf{1.00}$
$M_{Ed2} = \alpha_2 W_{Ed} l^2$	$\mathbf{0.009 \times 11^2 \times \boldsymbol{W_{Ed}}}$	$\mathbf{0.008 \times 11^2 \times \boldsymbol{W_{Ed}}}$
$M_{Ed2} < M_{Rd}$; $W_{Ed}\ (kN/m^2)$	$0.009 \times 11^2 \times W_{Ed} < 1.93$ $\boldsymbol{W_{Ed} < 1.77}$	$0.008 \times 11^2 \times W_{Ed} < 1$ $\boldsymbol{W_{Ed} < 1.03}$
$Total\ W_{Ed}$ (kN/m^2)	$\mathbf{1.77 + 1.03 = 2.80}$ $\boldsymbol{Under\ uniformly\ distributed\ load}$	
$Max\ UDL\ Moment$	$\boldsymbol{\frac{wl^2}{8} = \frac{2.80 \times 11^2}{8} = 42.4kNm}$	
$Max\ Triangular\ Moment$	$\boldsymbol{\frac{wl^2}{9\sqrt{3}} = \frac{w \times 11^2}{9\sqrt{3}} = 7.76w}$	
$Max\ Design\ Lateral\ Load$	$42.2 = 7.76w$ $\boldsymbol{w = 5.44kN/m^2\ (5.44kPa)}$	

Characteristic Shear Strength	$\sum(f_{vk0} + 0.4 \times \sigma_d)/2.5$ $= \dfrac{(0.2 + 0.4 \times 0.18) + (0.15 + 0.4 \times 0.176)}{2.5}$ $= \mathbf{0.197}\boldsymbol{N/mm^2}\ (\mathbf{197}\boldsymbol{kPa})$

Note that the static pressure head of 1m depth of water is 10kPa, meaning that the longest span wall can only safely take 0.5m water depth. However, this is also based on the assumption that there is no other structural element inside the house (i.e. partition walls). The addition of structural elements will shorten the span and therefore increase the safe design lateral load.

Table 5. Measured results by changing the distance (flood height for reference only)

Distance (m)	Maximum pressure (kPa)	Maximum shear stress for 11m wall (kPa)	Approximate maximum height of water (m)
0	32.3	118	4.93
5	31.1	114	4.91
10	30.7	113	5.30
15	32.8	120	5.81
20	28.8	106	5.54
25	29.1	107	5.84
30	33.0	121	5.71
35	28.2	104	5.60
40	28.2	105	5.42
45	28.5	105	5.72
50	32.0	117	5.91

Table 6. Measured results by changing the orientation (flood height for reference only)

Angle (˚)	Maximum pressure (kPa)	Maximum shear stress for 11m wall (kPa)	Approximate maximum height of water (m)	Position of max height
0	32.3	118	4.93	L-shape
45	29.0	106	5.11	L-shape
90	29.7	109	4.59	Front side
135	26.9 (25.5)	98.6 (93.5)	4.32 (4.80)	-
180	30.7	113	4.53	Front side
225	27.0	99.0	4.18	Front side
270	32.3	118	4.00	L-shape
315	33.0	121	5.01	L-shape

Table 7. Measured results by changing the flow velocity (flood height for reference only)

Velocity (m/s)	**Maximum pressure (kPa)**	**Maximum shear stress for 6m wall (kPa)**	**Approximate maximum height of water (m)**
0.1	9.00	33.0	2.00
0.5	22.4	82.1	3.77
1.0	32.3	118	4.93
1.5	39.3	144	5.39
2.0	45.9	168	Overtopping height
2.5	51.4	189	Overtopping height
3.0	56.6	208	Overtopping height

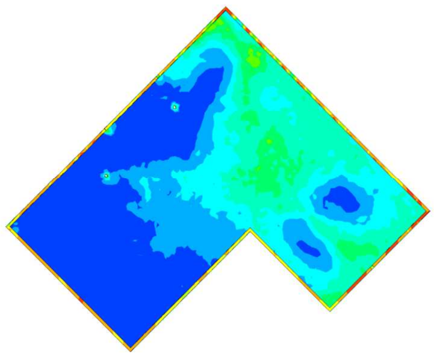
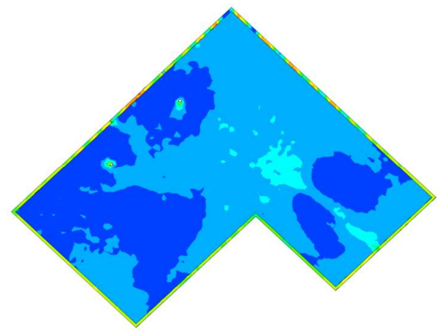
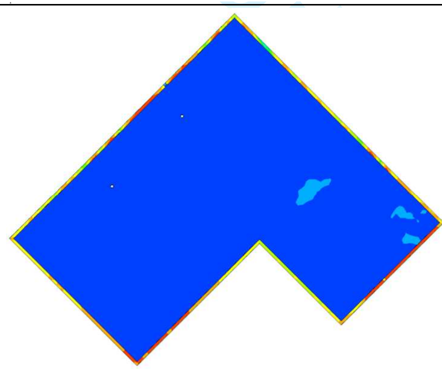
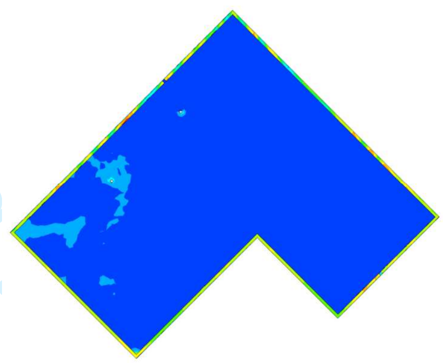
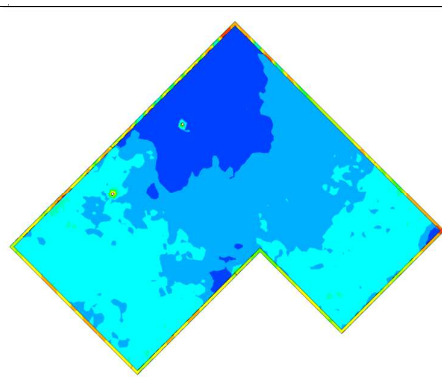
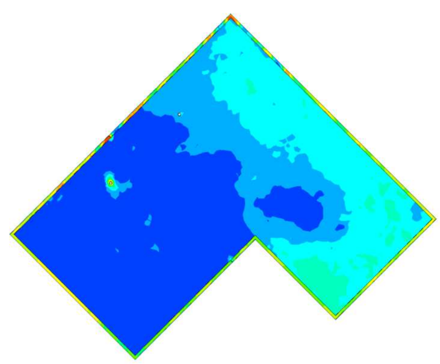
Table 8. Maximum pressure with flow velocity of 0.5m/s

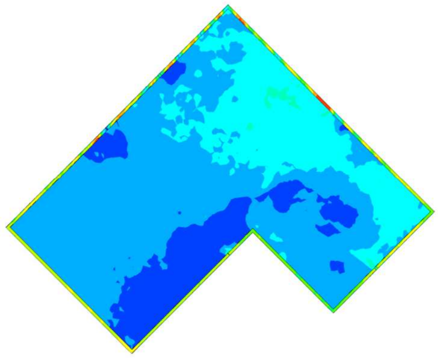
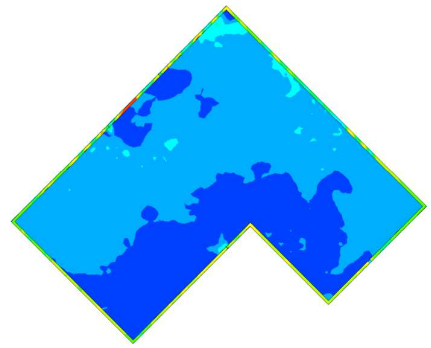
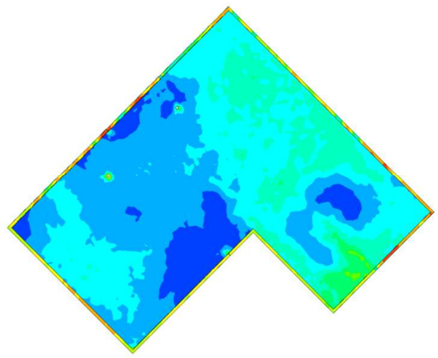
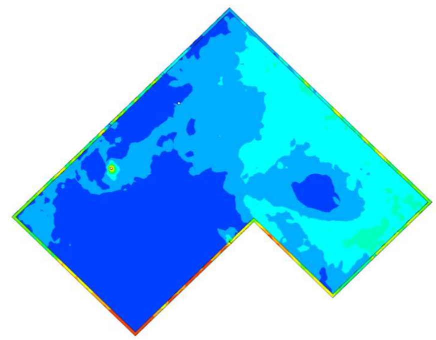
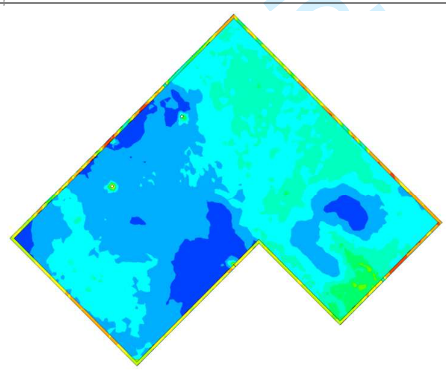
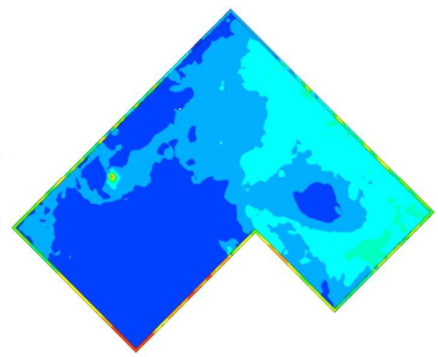
Distance (m)	**Maximum pressure (kPa)**
0	22.4
20	24.1
30	21.3

Table 9a. Summary maximum pressure after applying interventions

	20m	30m
No interventions	24.1kPa	21.3kPa
One floodgate	11.3kPa	9.15kPa
Two floodgates	14.0kPa	18.8kPa
Mortar sealing	14.6kPa	19.9kPa
Non-return valves	23.6kPa	17.6kPa

Table 9b. Results summary of applied interventions

Intervention	20m	30m
Front floodgate only		
Front and rear floodgates		
Mortar sealing		

Intervention	20m	30m
Non-return valve		
Timber flooring		
Concrete flooring		

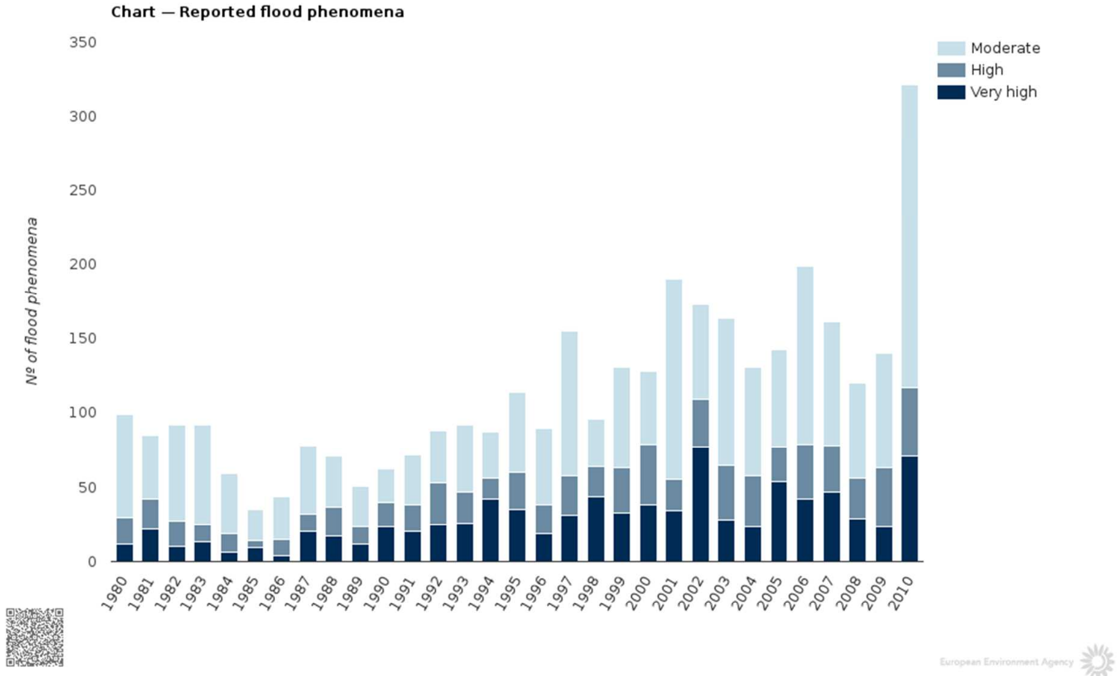


Figure 1 Reported flood phenomena in Europe from 1980 to 2010 (EEA, 2016).

Note: Flood severity is an assessment of flood phenomena magnitude. It considers the reported values on frequency, reported total damage (in Euros and descriptive classes), number of flood events within one flood phenomena unit and severity classes as reported in the Dartmouth Flood Observatory database (ETC/ICM, 2015b). All phenomena with fatalities are in the 'very high' severity class.

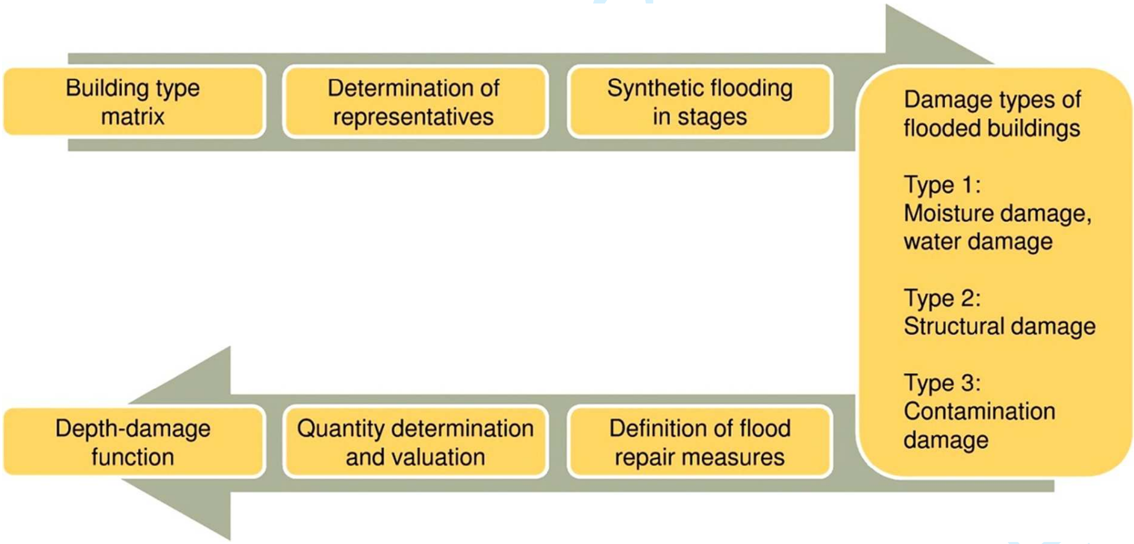


Figure 2 Methodological steps for the synthetic calculation of flood damage to buildings (Naumann *et al.* 2009 in: Golz *et al.* 2015)

impact parameters	damage types				
	structural damage of residential buildings	structural damage of road infrastructure	monetary loss to residential buildings	monetary loss to road infrastructure and companies	business interuption and disruption duration
flow velocity	NO	STRONG	WEAK	NO	NO
water depth	STRONG*	MEDIUM	MEDIUM	NO	MEDIUM
energy head	STRONG*	MEDIUM	MEDIUM	NO	WEAK
indicator for flow force	WEAK*	STRONG	WEAK	NO	NO
intensity	WEAK*	STRONG	WEAK	NO	WEAK

Fig 3. Qualitative summary of the influence of impact parameters on flood damage (Kreibich *et al.,* 2009).

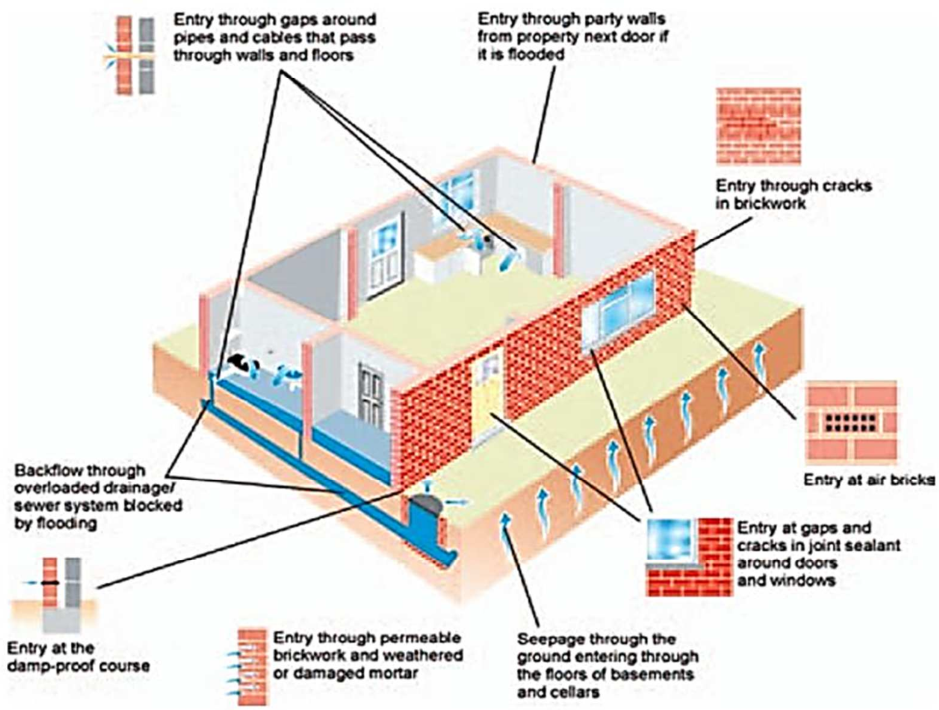


Fig 4. Possible pathways for ingression of floodwater (CIRIA, 2007)

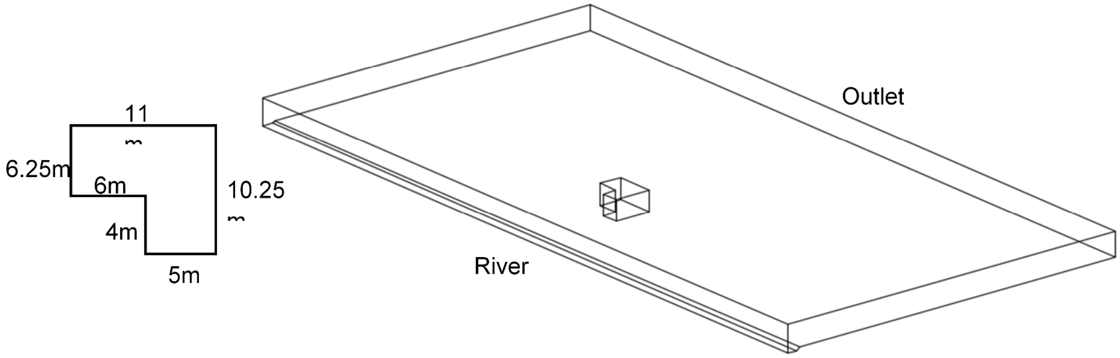


Fig 5a. House model dimensions and house in fluid domain

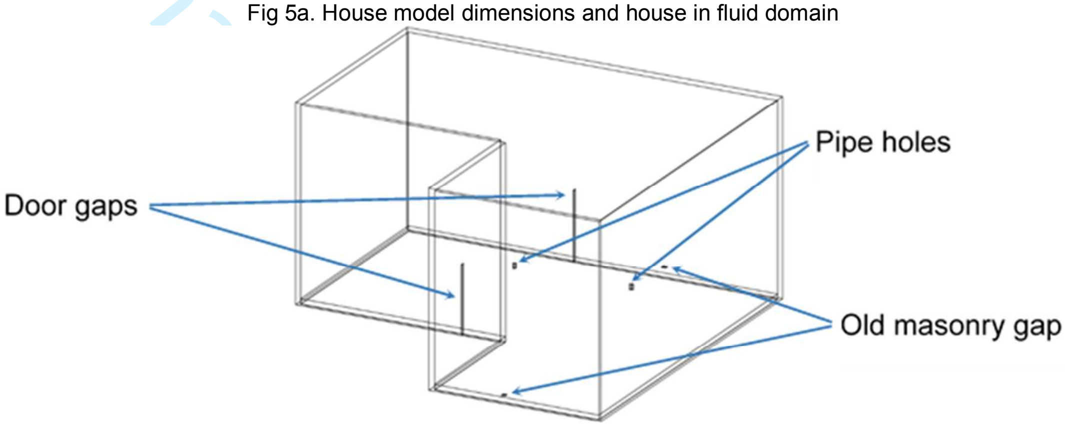


Figure 5b. Cavity house used for the interventions analysis (material specification and parameter absorption coefficient applied in ANSYS Fluent)

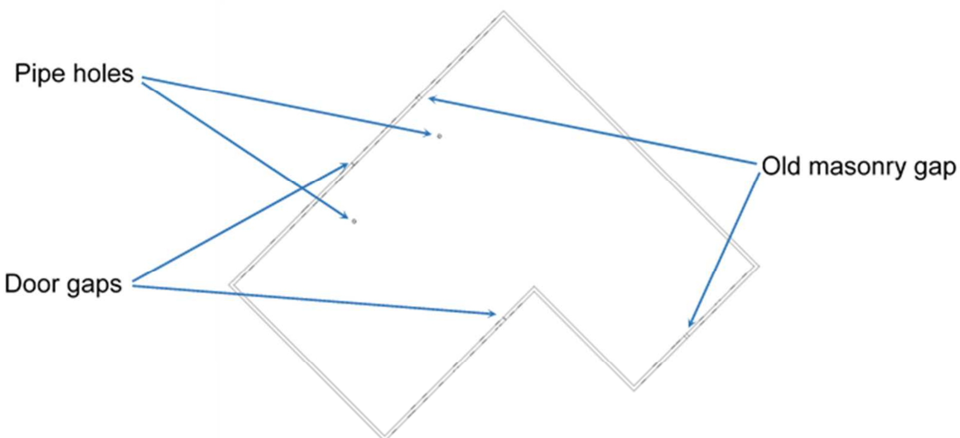


Fig 5c. Plan view of the hollow house

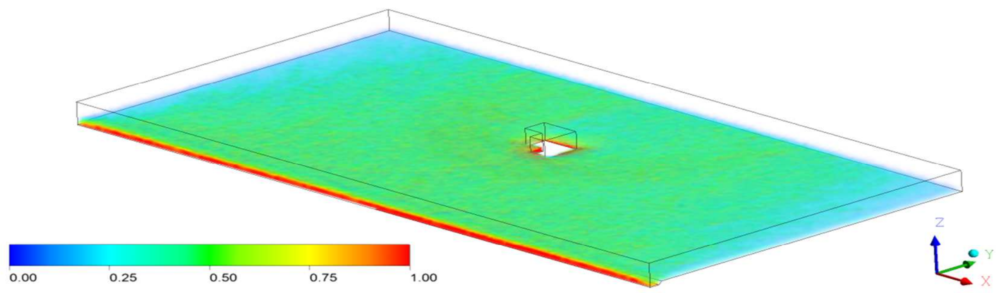


Fig 6a. House placed at 50m after 600s of simulation

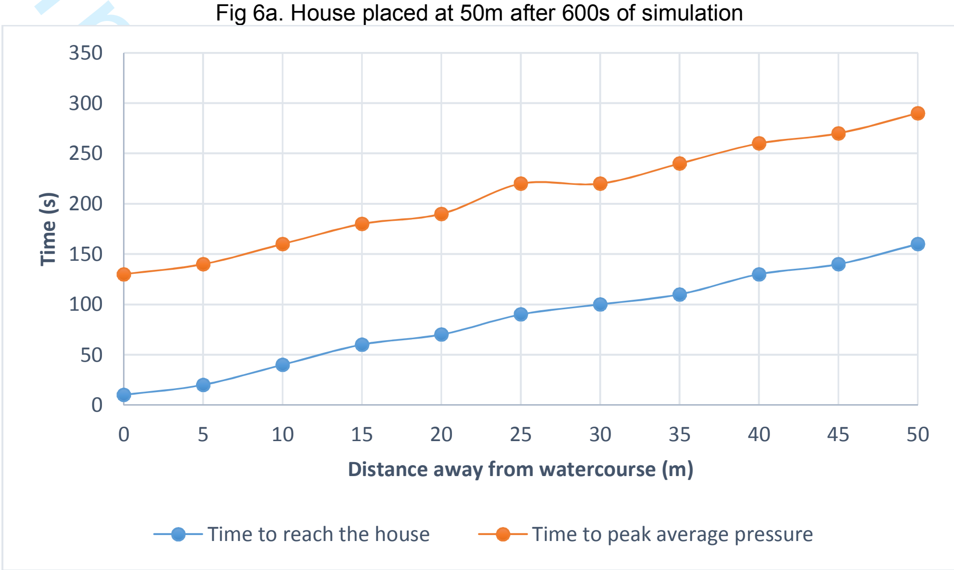


Fig 6b. Time taken for the water to reach the house and the time for the peak average pressure to act on the house

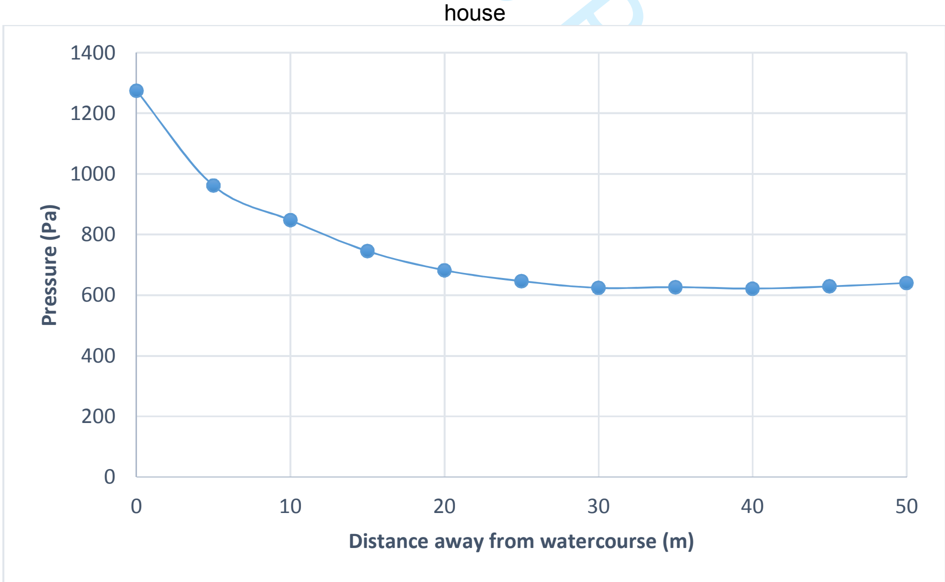


Fig 7. Average pressure after 440s

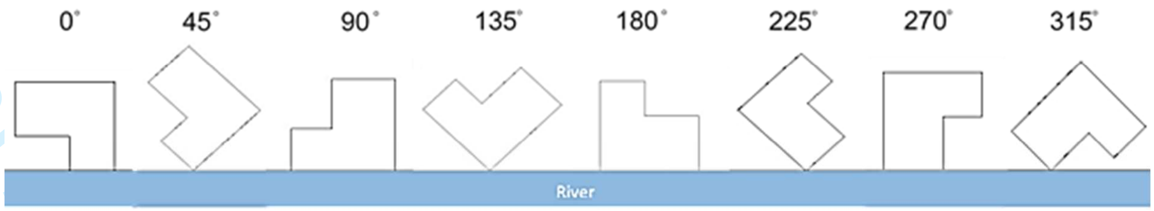


Fig 8. Plan view of house orientation placed in front of the river

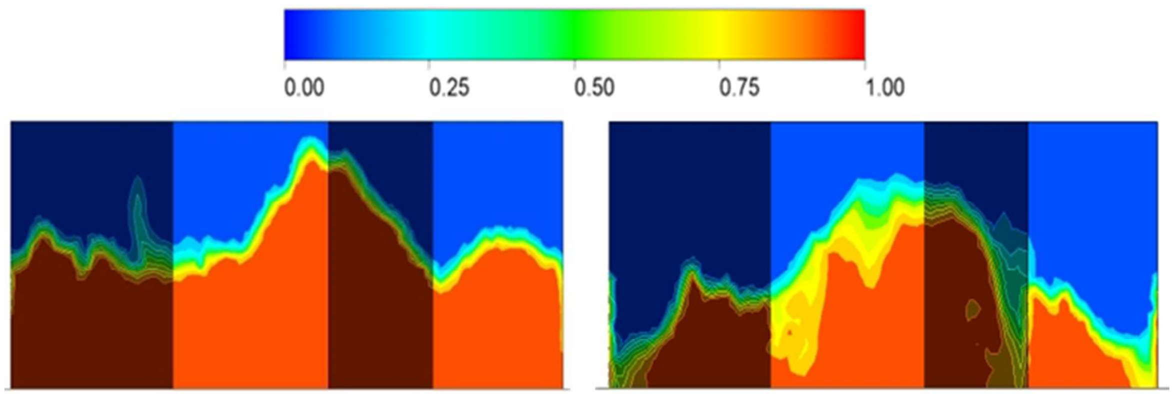


Fig 9. Maximum height of water relative to the house. Left to right: front of house 315˚ at 140s, back of house 135˚ at 180s

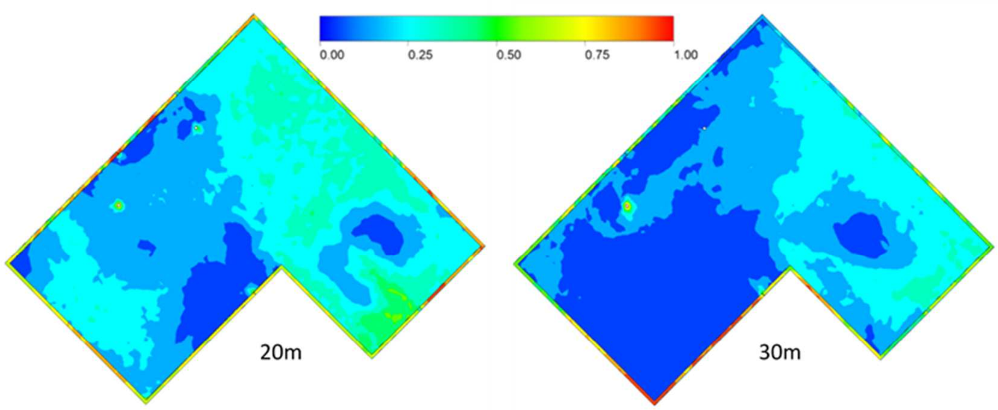


Fig 10. Contour map of water distribution on the floor after two hours of flooding with no intervention

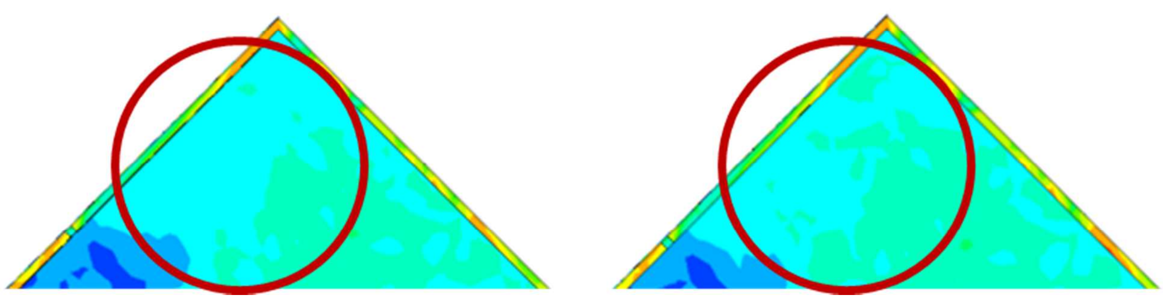


Fig11. Zoomed in contour map for a 20m house after two hours of flooding. Left to right: timber floor, concrete floor

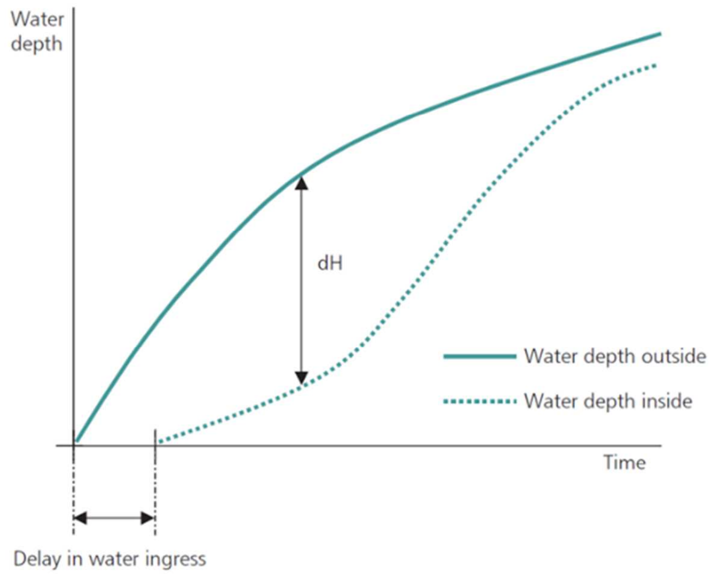


Figure 12. Conceptual illustration of flood water depths outside and inside a building with time (CIRIA, 2007)